THE USE OF RISK ANALYSIS BY THE U.S. ARMY CORPS OF ENGINEERS

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INTRODUCTION

Water related engineering has a long history of using risk analysis methods. Hydrologic engineers are very much concerned with risks in estimating the frequency of rainfall or stream flow events. In many situations, these engineering related risk quantities establish levels of "risk acceptance." For instance, the Flood Insurance Administration of the Federal Emergency Management Agency (FEMA) has used the 100-year or 1 percent exceedance flood as their "base flood." This risk standard implies that floods that exceed this standard (lower frequency floods) are too infrequent to worry about. In other instances, water agencies have used even rarer events for design purposes. The probable maximum flood (PMF) is frequently used as the design event for spillways. Among some hydrologic engineers, the PMF is so rare that its probability cannot be established; it is the last point in the tail of the flood flow frequency distribution. The purpose of the standard is to provide an operational design criterion to meet the engineering design goal of no failures. In these cases, the consequences of the event that exceeds the standard are not explicitly considered. For the FEMA case, the residents enjoying protection against the base flood might consider themselves "safe." Giving a dam a PMF spillway assures the engineer that the dam will never fail.

For the purposes of the following discussion, the terms, risk and uncertainty, need to be distinguished. These terms are frequently confused because the same terminology is used to describe each. A common definition of risk is the likelihood of the occurrence and the magnitude of the consequences of an adverse event. Uncertainty can be thought of as the indefiniteness of some aspect of the values in the risk quantification process. The term risk usually derives from some initiating "hazard" event with uncertainty characterizing the transmission of the hazard to the ultimate consequences.

The Corps of Engineers and other entities engaging in activities that manage risk have come to recognize that this purely engineering approach to risk management is too simplistic and incomplete. More than a single risk needs to be considered. These risks may stem from other engineering or technical considerations, environmental issues, or economic performance. In addition, when factoring risks into decisions, the Corps recognizes that uncertainties about the quantities in any part of an analysis must be addressed. The reason for using risk analysis is to make better engineering and economic decisions. This is accomplished by increasing our understanding of how Corps water resources investments will perform in the future from both engineering and economic perspectives.

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This does not imply that introducing risk analysis methods and thinking into a traditional engineering organization has been universally embraced. To address legitimate concerns about the necessary learning at the technical and managerial levels, risk analysis is being gradually applied in different civil works areas and the process is not complete.

The following three sections describe the agency wide usage of risk analysis by the Corps as of 1996. In the succeeding section, special applications are described. The paper concludes with a description of new directions and assessment of the Corps successes in using risk analysis.

DAM SAFETY

Civil engineers have a long interest in designing dams that can withstand unusual or rare loads due to floods. This interest in improving the reliability of engineering structures has been generally pursued by first quantifying the size of the rare event and then providing design features to assure safety. The National Research Council (NRC) report on dam safety (NRC, 1985) provides a synopsis of the evolution of design criteria for the safety of dams in the event of rare floods. The development of the notion of the probable maximum flood (PMF) represents a culmination of this evolution. This hypothetical event is considered to have virtually a zero probability of occurring. The basic philosophy of this design approach is similar to that used in regulating human health and safety risks: establish the standard at the dosage where there are no observed adverse effects. With dams, however, the adverse effects are to the dam and on humans only inferentially. Applying this "standard" to all dams ignores differences in the effects of dam failure at different sites.

Based on the NRC report, the PMF standard applied to all dams may be excessive. The report notes that "since the spillways of many existing dams are inadequate by PMF standards but have survived in spite of this inadequacy, it is legitimate to question whether this standard is higher than may be required." Additionally, the PMF inflow event is only one part of the chain of conditions assumed in designing to PMF standards. These include "conservative" assumptions about infiltration losses due to soil conditions, initial reservoir water levels, and reservoir operations. This compounding of highly risk averse assumptions may reduce the likelihood of the very rare flood to an absurdly small probability.

The problem that the Corps faced was applying the PMF standard to existing dams. Meeting the standard would require costly modifications to spillways and embankments. Risk analysis was considered as one approach to choosing whether to make a safety improving investments for any dam. One approach is to use a comparative risk analysis (Moser and Stakhiv, 1987). Under this method, accepted levels of risk to human health and safety are used as the design standard. This requires characterizing the dam safety risk by quantifying both the likelihood and the consequence of dam failure for the existing dam configuration and all modifications formulated. The fatal flaw for this approach is the wide error band for large floods calculated by extrapolating traditional flow-frequency relationship. In addition, getting beyond assigning a probability to the PMF proved insurmountable.

An alternative approach that was adopted used some ideas from risk analysis but without attempting to develop probabilities. Instead of relying on the PMF standard, the Corps defined a "base safety standard." This design standard is met ". . . when a dam failure related to hydrologic capacity will result in no significant increase in downstream hazard (loss of life and economic damages) over the hazard which would have existed if the dam had not failed." (USACE, 1985) Figure 1 shows an idealized result showing the base safety standard at less than the PMF. This policy espouses an "incremental hazard" viewpoint. Any dam modification to pass safely a PMF is excessive if a failure at a lesser flood has the same consequences as those if the dam had not failed. Thus, modifications that do not reduce the hazard or consequences of the event should not be considered further. An alternative interpretation is that it assumes the engineer should provide safety to the point that the dam does not impose an added risk compared with the natural situation. Although this approach to dam safety does use some risk analysis concepts, it does not provide information on the risk bearing by those downstream of the dam. The basic philosophy is that the engineer should not impose any added risk regardless how small. Of course without probabilities, there is no objective measure of the risk reduction produced by a modification to meet the base safety standard.

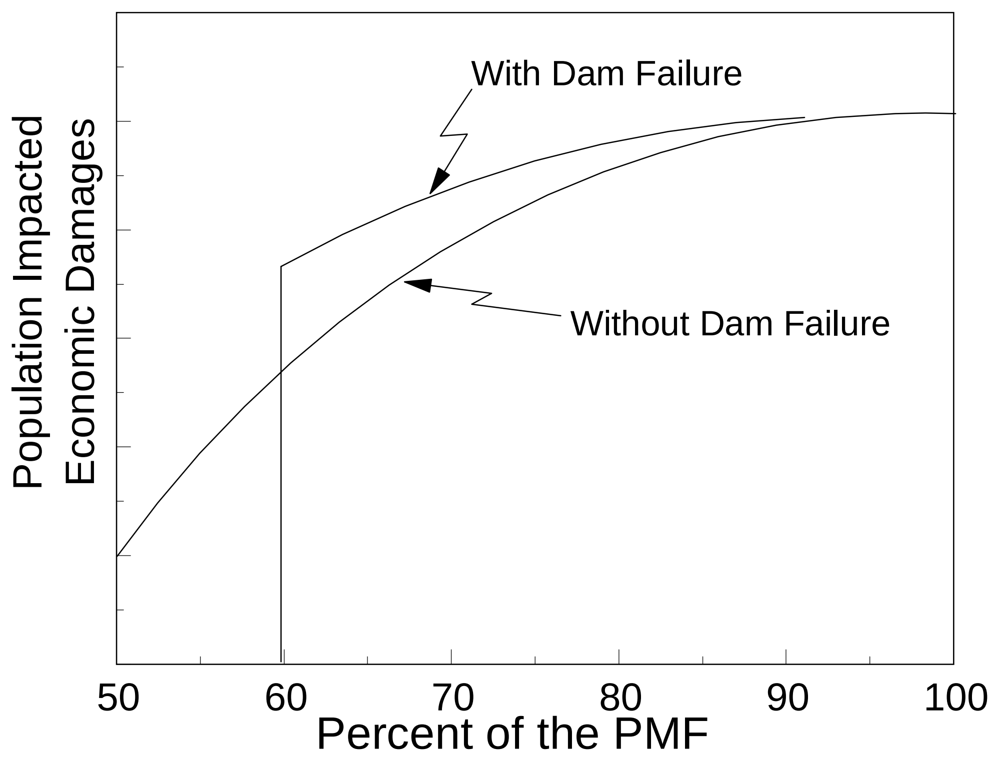

Figure 1: Determining the Base Safety Standard, USACE, 1985.

Estimating the "with and without" dam failure impacts requires quantifying the people and property at risk from various flood events. Models routing inflow floods through the reservoir and downstream routing of non-failure and failure flows are used. Characteristics of these events, especially warning time to population centers, are important in providing realistic estimates of people at risk. The procedures necessary to evaluate a dam safety hazard from rare floods are codified in USACE, 1986. These procedures describe the steps necessary to develop the input data to set the base safety standard as shown in Figure 1.

The Corps is now starting to examine its dam safety policy to consider all sources of dam failure risk, not just from rare floods. If quantifying all initiating event probabilities can be done, an overall statement of risk can be provided and the contribution to risk reduction of each dam modification assessed. Potentially, this might provide the basis for establishing a risk-based dam safety standard using a comparative risk analysis approach.

MAJOR REHABILITATION

The Corps of Engineers is responsible for managing hundreds of water resources investments throughout the United States. Many of these projects have performed successfully over many years and continue to provide valuable services to the nation. As these projects age, the years and wear and tear take their toll. Major components of projects become less reliable and are subject to both degraded service and the possibility of failure. In addition, new technology offers the potential opportunity to enhance the project outputs while addressing any reliability problems. In 1991, the Corps initiated the use of risk analysis to evaluate proposals for any major rehabilitation of water resource investments that it manages. Before that time, spending for major rehabilitation required little analysis of the likelihood or consequences of project component or feature failure. The Corps, with the encouragement of the Office of Management and Budget (OMB), recognized that major rehabilitation is an investment to avoid future increased operating and emergency repair costs and losses in project outputs due to emergency repairs. To implement the program, the Corps developed an economic-based decision framework that borrows heavily from the methods of risk analysis combined with probabilistic benefit-cost analysis (USACE, 1996).

Quantifying future project component or feature reliability is fundamentally an engineering problem. For investment and rehabilitation decision making, however, the consequences of future unreliable engineering performance must be related to economic consequences and the economic performance of the project being evaluated. To help identify the linkages between risk and consequences, analysts must use standard risk analysis tools such as event trees and fault trees. These trees are frequently used together to expose the process of transmitting risks to consequences and to identify required contributions from each member of the study team.

To place this into a benefit-cost framework requires the establishment of the "with and without" project condition. Since the project is already in operation, the "without" project condition is "without" major rehabilitation, defined as the base condition. Completing the analysis requires a determination of the response to actual breakdowns and an assessment of the economic costs during these "unplanned" situations. Major rehabilitations reduce the frequency of these breakdowns, the cost of the breakdowns or both. Besides reducing future project costs, major rehabilitations offer the opportunity to restore project efficiency lost since original construction and to increase project outputs beyond the original design. Therefore, the economic benefit of rehabilitation is composed of the reduced future costs and the value of increased future project output. Rehabilitation costs obviously contain the cost of constructing the rehabilitation alternative chosen. Less obvious is the cost in the form of lost project outputs during the time that the project is closed during the rehabilitation. This last cost is frequently overlooked but also can be reduced by careful planning and scheduling of the construction.

A life-cycle approach was adopted in recognition that a major rehabilitation makes a sure investment that must be balanced against uncertain, future reductions in costs and increases in output. Additionally, component reliability may change with time and usage. The variable of interest is the present value of rehabilitation benefits. Analytical or simulation models must be employed to evaluate the base condition and all rehabilitation strategies to predict benefits. Typically, Monte Carlo simulation models have been developed or adapted to estimate the distribution of life-cycle benefits. Initially this involved the use of general purpose tools such as spreadsheet macros and spreadsheet Monte Carlo simulation add-ins such as @RISK by Palisade and Crystal Ball by Decisioneering. As problems become more complex, special purpose models have been developed.[2]

Quantifying the reliability of engineering features and components has required adaptation and development of new methods. The initial approach, at least for structures, used a reliability method for quantifying a reliability index of a component or feature. This method relied on the availability of models predicting the safety factors for features of interest. The capacity and demand aspects of the safety factor model are based on values of input variables such as thickness of metal and unit weight of concrete. Any uncertainty in these input variables will result in an uncertainty in the safety factor. This approach only provides a snapshot of the reliability of the feature. Because a major rehabilitation changes the future reliabilities, a weak link in the reliability index method is its inability to forecast future reliabilities. To develop time or usage dependent reliabilities, capacity models containing time or usage variables are being developed to replace the reliability index method. For components with systematic records of failure, survivor analysis is used to estimate a hazard function for a component. The hazard function provides the age or usage dependent risk quantities required for a life-cycle analysis. This approach has been applied to hydroelectric generating unit components.

Quantifying the monetary values of operations and maintenance cost, repair costs, project outputs, and rehabilitation costs are straightforward. Estimating the uncertainties in these values is currently not required. However, in the future, these additional uncertainties may be added to the analysis.

The current policy is to recommend the rehabilitation strategy that has the largest positive expected net economic benefits. Thus far, approximately 20 major rehabilitation reports have been

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[2]See for example Moser, et al, 1995 and USACE, 1994.

submitted supporting major rehabilitation spending of about $600 million. Due to budget limitations, not all these projects have received funding. Reports approved so far have been primarily for rehabilitations of hydroelectric and navigation machinery and equipment. One distinguishing aspect of rehabilitation analysis results for hydroelectric projects is the importance of non-reliability related benefits. These stem from the opportunity to "uprate" electric generation capability during a major rehabilitation. The benefit from reducing unreliability in these projects comprises only 5% to 20% of the total, which is never sufficient to cover the major rehabilitation cost. This compares with reliability related benefits of nearly 100% for major rehabilitations of other types of projects. Not all projects studied for major rehabilitation have produced reports supporting major rehabilitation. This implies that a "fix as fail" strategy is the most economically efficient response to unreliable performance in some cases. Additionally, spending to rehabilitate some features or components has been shown not to meet the expected net benefits test.

The Corps major rehabilitation program has successfully applied risk analysis principles to investment decisions about aging hydraulic structures. Fortunately, the Corps has not faced the difficult decisions involving human health and safety as in dam safety. Major rehabilitation primarily is about financial risks where the use of an expected value decision criterion is usually appropriate.

FLOOD DAMAGE REDUCTION

The Corps of Engineers has used a risk analysis approach to flood damage reduction project evaluation for decades. A statistic, expected annual flood damage, is estimated by computing the area under a flood damage-frequency curve. This curve or function is derived by combining a discharge-frequency function, with stage-discharge and stage-damage functions shown in Figure 2. The frequency-damage function provides a concise representation of the risk; likelihoods are from the discharge-frequency function and the adverse consequences are the damages. The Corps has relied only on the expected value statistic to represent the economic performance of any flood damage reduction alternative. Hydrologic and hydraulic engineers and economists have long recognized that this computation ignores large uncertainties in the discharge, stage, and damage. To account for uncertainty in discharge, the Corps adopted an "expected probability" approach following an interagency committee recommendation.[3] (IACWD, 1982) This does not quantify the uncertainty in the discharge and carry it forward. Instead, the expected probability adjustment increases the deterministic discharge for rare flows attempting to account for the sparsity of historical data. Uncertainty in the stage calculations was recognized but not quantified. Hydraulic engineers adopted a risk management strategy of adding freeboard on dams and levees to be assured of passing the uncertainty stage of the design flow. Uncertainty in damage was ignored.

[3]For a discussion and further references on the debate about the use of expected probability see NRC, 1995.

In 1991 the Corps adopted a more thorough risk analysis approach to the engineering and economic evaluation of all the flood damage reduction projects it plans and builds.[4] There were several reasons for developing and carrying out this methodology. First, often the Corps added a "standard" freeboard to projects without trying to quantify the error in stage. At some locations the standard freeboard effectively provided more protection than claimed. Second, the practice of hydraulic engineering had not progressed with the science. The science had become more statistically oriented and the models for predicting stages more sophisticated than presumed by the simplistic addition of freeboard. Third, freeboard provided added engineering reliability and economic benefits that were frequently not properly accounted for in project performance evaluations. Fourth, single indexes of engineering performance, (e.g., level of protection), and economic performance, (e.g., benefit-cost ratio) convey a false impression of certainty. These single numbers masked a large amount of uncertainty about the performance of projects.

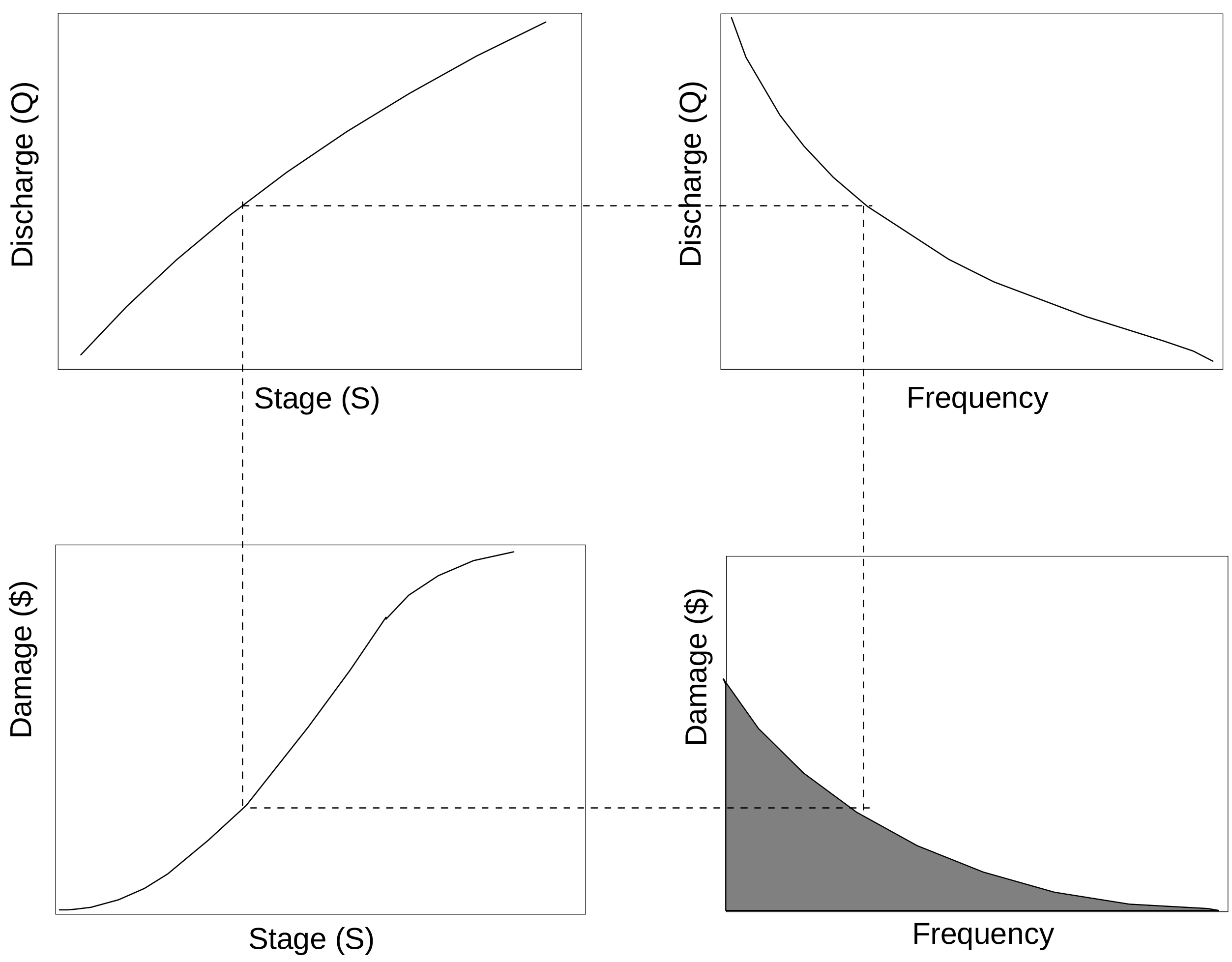

Figure 2: Frequency-Damage Estimation

[4]For current policy and procedures see USACE, 1996 and USACE, 1996b.

Current Corps policy requires the use of risk analysis methods for all flood damage reduction projects. The policy emphasizes concentrating on the uncertainty in variables that are key to project recommendation. Key variables enter the analysis by influencing uncertainty in flood discharge, flood stages, and flood damage. By quantifying these uncertainties, the measures of project performance can include a complete statement of risk and uncertainty. Specific uncertainties that must be addressed are discharge associated with exceedance frequency for hydrologic studies, conveyance roughness and cross-section geometry for hydraulic studies, the reliability of existing protective structures, i.e., existing levees, and stage-damage function for economic studies. (USACE, 1996). The basic approach advocated is to identify and quantify the uncertainty in the variables that contribute to prediction of discharge, stage, or economic damage. These uncertainties are then combined using the traditional engineering-economic model for estimating damage-frequency as shown in Figure 2.

Plan	Residual Annual Probability Exceedance	Equivalent Annual Cost
W/O Project	0.250	0.0
20 foot Levee	0.020	300.0
25 foot Levee	0.010	400.0
30 foot Levee	0.001	550.0
Channel	0.025	300.0
Detention Basin	0.030	275.0
Relocation	0.100	475.0

Table 1: Risk-Cost Tradeoff

The Corps has developed several generations of computer software tools to combine the uncertainties. These all rely on Monte Carlo simulation to derive resultant distributions of damage reduced and to describe engineering reliability. The latest computer software incorporating risk analysis into flood damage reduction project evaluation is described in Burnham, 1996.

The Corps risk analysis approach provides a more thorough description and can provide more understanding about the engineering and economic performance of any flood damage reduction alternative. National economic development (NED) remains the Corps decision rule for project selection. The risk information generated can provide the basis for a deviation from the NED plan to meet a reliability goal or a cost constraint. For instance, Table 1 shows the risk-cost tradeoffs for several flood damage reduction plans. The NED plan might be the 20-foot levee but the local cost sharing partners might find the residual risks unacceptable. They may be willing to pay the additional $100k per year to pay for the construction of the 25-foot levee.

Table 1 shows only one aspect of the information developed from a risk analysis. In fact, care must be taken to avoid invalid comparisons since this table shows only one tradeoff between plans. Other tradeoffs, such as risk versus population exposed, may differ between plans. This can occur if a plan opens land to development by providing protection against the FEMA base flood. Alternatively, exceedance of a plan may have small consequences such as a channel improvement.

The Corps use of risk analysis attempts to provide better information to improve decisions making. As stated in ER 1105-2-101:

> "All project increments comprise different risk management alternatives represented by the tradeoffs among engineering performance, economic performance, and project costs. These increments contain differences in flood damage reduced, in residual risk, and in local and Federal project cost. It is vital that the local customer and local residents understand these tradeoffs in order to fully participate in an informed decision-making process."

SPECIAL RISK ANALYSIS APPLICATIONS

Not all uses of risk analysis by the Corps fall into the categories where formal policy guidance exists. Risk analysis methods have provided the only means of trying to answer specific questions for individual projects Three specific examples provide an indication of the scope of Corps practice.

One application involved estimating the reduction in vessel collision and grounding damages due to widening of the Houston Ship Channel, (Moser, et al, 1995). Reducing these damages is a benefit from the channel improvement beyond the traditional shipping cost savings. The characterization and quantification of the likelihoods and consequences, with uncertainty involved several steps. First, historical casualty rates for the project site were calculated from U.S. Coast Guard records. The year to year variability was also calculated. Second, the distribution of casualty damages by casualty type was estimated from the same records. These were verified and adjusted based on interviews of affected parties from a sample of recent casualties. To quantify the risk reduction from channel modifications, subjective probability assessment elicited the risk reductions from a group of experts including the U.S. Coast Guard, the local pilot associations, and representatives of barge companies. Uncertainties, including uncertainties in the risk reductions, were carried forward to derive a distribution of casualty reduction benefits.

A second application estimated the risk of closure of the Poe Lock, Sault Ste. Marie, Michigan. Of particular interest was the likelihood of an extended lock closure from a vessel related incident. Vessel collision, fire and explosion, and lock gate impact, among other events were considered in this conventional risk analysis application. Weather and human error were also considered as contributing factors. None of the events has ever occurred at the lock. Throughout the world, the occurrence of any of these event is rare. A group of vessel masters, shippers, and lock operators was used to develop event trees mapping the process from initiating events to the terminal event, the length of lock closure, resulting form vessel incidents at the Poe Lock. With these event trees, a structured subjective probability assessment method was used to elicit probabilities of initiating and contributing factors from this same group. Additionally, the length of closure resulting from each terminal event was elicited from the experts. Divergence of options about probabilities and times of closure were carried forward and included in the uncertainty description of the results. Finally, the event trees and the probabilities were used to calculate the probabilities of different closure durations.

A third ongoing application uses risk analysis to evaluate an existing Corps requirement to provide an emergency closure system for hydroelectric unit intake gates that can stop the flow of water within ten minutes of activation. The requirement is intended to prevent extensive damage to a generating unit and possibly the powerhouse. At some hydropower projects in the Pacific Northwest, emergency closure times are longer due to alterations to improve water flow to divert juvenile fish. The study will help decide if costly modifications to achieve the closure time goal are worth the investment. Extensive event trees and fault trees were developed tracing initiating events to terminal events, possible damaging events. Probabilities of time to closure for different damaging events have been developed for different physical configurations of powerplants, representative of different Corps projects. Damages, including the cost of replacing lost power during repairs, have been estimated for different damaging events and times to closure. A survey of Corps and non-Corps hydropower projects developed estimates of historical frequencies to calculate the probabilities of the terminal events. These were then supplemented using subjective probability assessment by an expert panel representing machinery manufacturers, power producers, experts in installation and repairs, private powerhouse insurers, powerhouse operators and powerplant designers. A Bayesian analysis was used to combine the estimated historical frequencies with the expert judgments. Combining the probabilities of duration of damaging events with damages as a function of durations, expected annual damages were estimated for each of the powerhouse configurations. The preliminary results suggest that modifications in emergency gates can be cost effective for some sizes of powerhouses and some powerhouse configurations.

EXPANDED USE OF RISK ANALYSIS

The Corps of Engineers is pursuing expanded application of risk analysis methods. Coastal protection projects are similar to flood damage reduction projects in many respects, offering a natural opportunity to apply risk analysis. An important distinction, however, is the cumulative impacts of storms on a coastline. To address this issue, a life-cycle approach, using Monte Carlo simulation to combine uncertainties is proposed. Deep draft navigation investments display many engineering and economic uncertainties that can influence the identification of economically efficient investments. The Corps is developing approaches, models, and evaluations that account for uncertainty in forecasts of commodity flows and vessel fleets, dredging costs, and dredged volumes. Risk analysis applications to shallow draft navigation investments are also under development.

Operating and maintaining existing projects now accounts for over half the Corps civil works budget. To more efficiently allocate scare resources, risk analysis approaches are being considered to help balance project reliability and economic value against operations and maintenance costs.

Expanding the use of risk analysis has its critics within the Corps. Partly this stems from the added study costs as practitioners learn new methods and ways of thinking. As learning grows and as new models are developed, meeting risk analysis requirements will be less costly. By quantifying uncertainties and explicity including them in the evaluation, some studies may be completed without the high cost of collecting some primary data, resulting in lower study costs. These benefits are speculative at this time, however. Criticism of adopting risk analysis approaches also arises from skepticism about the "value added" of the analysis. Critics argue that if the method does not change the answer, the Corps should not go to the expense of conducting the analysis. Sometimes, the answer is different, but not always in the direction of less costly projects. Large uncertainties in flood flows can lead to projects larger than that proposed in a deterministic analysis. An additional value added is a better understanding of how a project can perform. This can be very valuable in helping cost-sharing partners and potential beneficiaries make better decisions. A final criticism of risk analysis is the difficultly of communicating information about project performance in terms of means, variances, and probabilities. These critics argue that the lay audience will not understand and are not interested in uncertainties and risk. This is a frequent and, partially, valid criticism of risk analysis. Decision makers and the public need to be enlightened, not confused. Techniques for communicating risk information are improving and the public is becoming more accustomed to information couched in risk terms. There is a need to spend more effort adopting terminology and displays of risk analysis results that recognize the sophistication of the audience.

CONCLUSION

The Corps of Engineers has used risk analysis techniques and ideas for many years. It has only been in the last decade, however, that risk analysis methods have been explicitly integrated into decision making. This integration has provided the risk-cost and risk-net benefit tradeoffs, and distributions of net benefits. These provide additional information for decision making and a better understanding of how a water resource investment works. Given this information, better decisions can be made. By explicitly examining risk-cost tradeoffs, the Corps is reconsidering the value of requiring some standard assumptions and criteria in all instances. Allowing some flexibility can reduce project costs will only small sacrifice in project performance.

Note: All opinions expressed are those of the author and do not necessarily represent the policy of the U.S. Army Corps of Engineers.

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